Review of the homodyne technique for coherent radar

Christensen, Erik Lintz; Madsen, Søren Nørvang; Skou, Niels

Published in:
Record of the IEEE International Radar Conference

Link to article, DOI:
10.1109/RADAR.1990.201155

Publication date:
1990

Document Version
Publisher's PDF, also known as Version of record

REVIEW OF THE HOMODYNE TECHNIQUE FOR COHERENT RADAR

E. Lintz Christensen, S. Nørvang Madsen, and N. Skou
Electromagnetics Institute, Technical University of Denmark

ABSTRACT

The homodyne technique using modulation and demodulation directly on the radiated carrier is not used much for various good reasons. However, when broadband coherent systems are considered, most of the advantages of the heterodyne approach vanish and it becomes realistic to contemplate the advantages of reduced complexity and fewer bandwidth limiting components of a homodyne system. The influence of various component deficiencies is discussed with relation to the choice between homodyne and heterodyne. Measurement results on quadrature modulators and demodulators at 300 MHz and 5.3 GHz are given to support that the homodyne technique can be applied successfully.

INTRODUCTION

The technique used in the first radio devices was homodyne in the sense the concept will be used here, i.e. the information to be transferred by a radio carrier was modulated directly on the carrier radiated, and the information was extracted again by demodulation of that carrier. The homodyne technique was abandoned for most applications in particular because amplification and selectivity were hard to get at the frequencies needed for proper utilization of the radio spectrum.

It may be proper to recapitulate the merits of the heterodyne technique over the homodyne technique. At high radio frequencies amplification is expensive and the noise performance is poor. Mixers (followed by amplification at lower frequencies) may offer better performance in spite of their inherent conversion loss. However, what may be called high frequencies in this respect changes with time, and today amplifiers offer better noise performance than mixers even above 10 GHz although they may not be price competitive at these frequencies. Furthermore, filters are increasingly expensive and offer poorer selectivity (in terms of absolute bandwidth) at the higher frequencies, but here the requirements change with time. Applications such as spread spectrum communication and high resolution radar need bandwidths which are not too narrow for direct filtering. Actually filtering at the radio frequency may not be necessary at all - this depends on the interference tolerance and many other application specific parameters.

Now and then applications appear where it seems advantageous to reconsider the merits of the homodyne technique, and the high resolution coherent radar might well be such a case.

MODULATION, UP-, AND DOWN CONVERSION

The fundamental principle of coherent radar is that a signal with a known complex spectrum is radiated, received and processed. The signal may be generated directly at a certain carrier and the processing may similarly take place at a carrier. This is the case for the well known SAW device [1] used for chirp generation and pulse compression, and for the generation of linear chirp by a sweep oscillator combined with de-ramp processing ("strech processing") in the receiver [2].

The signal may also be generated and processed at baseband as a complex signal consisting of I and Q components which must then be transferred to/from a carrier for radiation. This analog modulation/demodulation process, and the question whether to perform it directly at the frequency to be radiated (homodyne), is the topic of the present paper. As an alternative to the IQ scheme, the signal can be generated as a digital signal on an off-set carrier, which is then D/A converted using a single D/A converter. After reception the signal is A/D converted using a single A/D converter and the final carrier is removed digitally. This method it capable of very good performance but the bandwidth is limited by the speed of the D/A and A/D converters and further frequency conversion is inevitable with to-days technology.

When the spectrum has been shifted away from zero, further up- and down conversion of the carrier frequency is relatively easy since simple mixers can be used and the excessive spectral components can be removed by linear filtering. Using the same stable oscillator for up- and down conversion alleviates the oscillator stability requirements. This means that the nonlinear signal processing can be performed at the frequencies where it is considered best independent of the frequency required for the radiated spectrum. It also means increased complexity with a penalty in cost, reliability, and performance which must be traded against the advantages.

COHERENT TECHNIQUES

The coherent techniques require per definition that the receiver has knowledge of the phase of the transmitted signal (at least the phase of the carrier but for radar also that of the code modulated on that carrier). The information to be obtained by the system is then to be extracted using this phase. In other words the information is (partly) the deviation of the phase of the received signal from that of the phase reference, and the ultimate information extraction takes place at base band, i.e. the carrier frequency is transferred to zero, where the information will be available as two orthogonal signals, the I and Q signals.

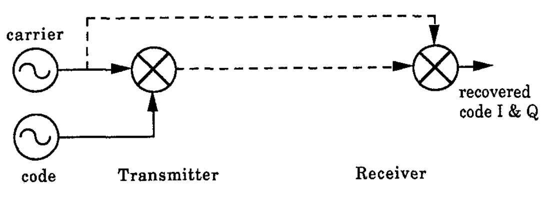

Figure 1. Simple homodyne scheme

CH2882-9/90/0000-0159$1.00

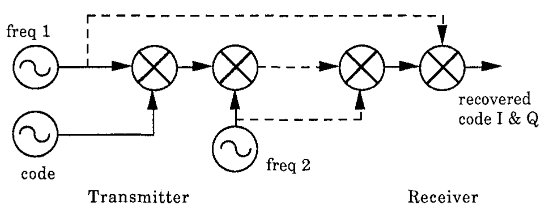

Figure 2. Simple heterodyne scheme

The obvious choice of detection scheme for this configuration is the homodyne technique, where the received signal is multiplied with the carrier directly as indicated in Fig. 1, rather than the heterodyne scheme. The heterodyne scheme requires several references and multipliers as indicated in Fig. 2, and it must be remembered that simple multiplication will not do the trick since single sideband conversion is required. The image frequency must be suppressed by a filter or an image rejection mixer at both sides. The trade offs usually leading to selection of the heterodyne approach in spite of the additional components are different from application to application, but the major issue is that real life components are far from ideal.

HOMODYNE VERSUS HETERODYNE

Assuming ideal components there would be no reason at all to use the more complex heterodyne principle. The code to be transmitted is transferred (by the modulator) directly to the carrier frequency without any by-products , and the receiver transfers (by the demodulator) the signal to base band where the filtering needed to reduce the noise bandwidth may take place. The carrier frequency can be changed freely. The same features are available from the heterodyne approach, provided single sideband conversion is used, however using more components.

The weak point in the homodyne system is the single sideband converter, or IQ modulator/demodulator as it is called when one of the frequency bands is centered around zero. It has several deficiencies:

- In order to perform the multiplication process (needed for the modulation) one signal (the carrier or the reference) must be large enough to create harmonics. These harmonics cannot be allowed to reach the antenna as they will disturb other services but they are fairly easy to remove by filtering and an octave band of instantaneous frequency tuning would still be possible.
- The carrier will leak through the modulator. This gives an in-band signal, and the permitted amount is specific to the application. A corresponding problem in the demodulator is a DC component in the demodulated signal.
- Harmonics of the smaller signal (the code), or intermodulation products if a more complex signal is to be modulated onto the carrier, cause some in-band and some out-of-band distortion products, of which the latter may be difficult to remove by filtering, since the relative bandwidth can be quite small. Similarly in-band intermodulation products are likely to cause problems in the demodulator.
- 1/f noise of microwave semiconductors used for modulation and demodulation can bring up excessive noise, but this is not a serious problem with modern components used in broadband applications.

The heterodyne technique, which also rely on the IQ modulator/demodulator, does not remove these problems but allows some of them to be tackled at lower frequencies. When the modulation and demodulation takes place at a lower frequency, and especially at a fixed frequency, the devices might perform better. The deficiencies still present at the high frequency conversion (mixing) will be out-of-band, if the intermediate frequency was properly selected, and is easily removed by filtering.

Even if the modulator and demodulator for the homodyne approach were inferior to those of the heterodyne the overall performance of the homodyne system may still become the better. Furthermore, experiments indicate that the high frequency of operation of the homodyne components is not a bigger obstacle than the high relative bandwidth of the heterodyne components, at least for high resolution radar applications.

DIGITAL SIGNAL PROCESSING

The introduction of digital IQ signal generation and processing makes it feasible to correct for some of the problems of modulator and demodulator design by pre-distortion, offset correction etc. [3]. These corrections can be applied to a homodyne system as well as to a heterodyne system. However, since the desired performance parameters for some applications may be more difficult to satisfy by IQ modulators and demodulators for a homodyne system these corrections might be even more relevant and important in relation to homodyne systems.

In the digital signal generation process digital pre-distortion can be implemented without additional hardware since the same pre-distorted digital signal is used repeatedly. This applies to corrections for transfer function errors (IQ common as well as differential) and individual bias corrections. However, some errors may not be compensated by baseband pre-distortion at all, namely odd (relative to the reference signal frequency) amplitude differences between the modulated I and Q channels. Pre-distortion in the transmitter for errors in the receiver is unfortunately not feasible since the power amplifier in nonlinear.

The situation is somewhat more complex in the receiver since the signal is different from scan to scan. Only common mode transfer function errors can be corrected without adding extra digital processing hardware. Similarly quadrature errors can be corrected but at the expense of added digital hardware.

THE COHERENT RADAR

The radar to be used here as example is a 5.3 GHz synthetic aperture radar designed for strip mapping at high resolution [4,5,6]. The first test flights with this radar took place late 1989, while the baseline design was fixed in January 1987. A heterodyne approach was chosen with an intermediate frequency of 300 MHz partly due to uncertainty as to the performance of a homodyne system, partly because that allowed for a SAW chirp generator as a back-up solution if severe problems with the digital signal generator should appear. The bandwidth of the signal is limited to a little less than 100 MHz by the maximum rate of the A/D converters (8 bits, 100 MHz, I or Q). A rough outline of the relevant parts of the receiver and the transmitter is shown in Fig. 3

Each of the components of the radar contributes to the degradation of the final result. For SAR applications these degradations are described by impulse response (IPR) broadening and the sidelobe levels i.e. the peak sidelobe ratio (PSLR), and the integrated sidelobe ratio (ISLR). IPR broadening is caused primarily by the quadratic components of the complex transfer function versus frequency and the quadratic phase deviation will be the least for a fixed absolute bandwidth symmetric filter if the relative bandwidth is small. This speaks in favor of the homodyne system.

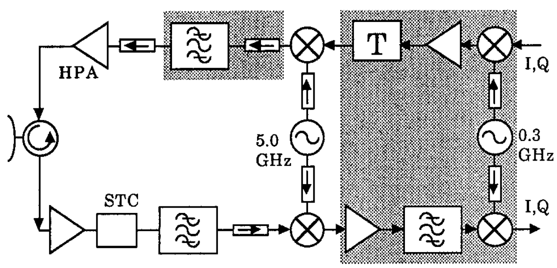

Figure 3. Outline of radar transmitter and receiver

The design goal of the radar in question is: PSLR < -35 dB and ISLR < -25 dB as the total level for both range and azimuth sidelobes (i.e. -28 dB ISLR for each). At the time of writing it has not yet been verified whether the complete system reaches this goal although it is known that the components discussed here are capable of that performance and preliminary tests of the complete system seems to certify this fact [6].

A homodyne approach would make it possible to remove the components in the shaded boxes and replace the 5 GHz mixers with 5.3 GHz IQ modulator and demodulator, and add two amplifiers at 5.3 GHz. The filter needed to limit the noise-bandwidth to 2% is not a serious problem and the same can be said of the additional amplifiers (for the case of the example system the amplifiers required are: receiver: 23 dB gain at -12 dBm output, transmitter: 9 dB gain at 12 dBm output).

The benefits are reduced complexity and improved frequency response provided the modulator and demodulator can be made with sufficient suppression of the carrier, the image frequency band, and distortion products of the baseband signals. In order to compare these performance parameters at the two frequencies a modulator/demodulator pair was constructed for 5.3 GHz operation.

IQ MODULATOR AND DEMODULATOR

The IQ modulator and demodulator are based on the same principles. They are each based on two balanced mixers used to multiply the input signal with a reference oscillator signal.

They rely to a high degree on the mixer balance for suppression of the reference signal which appear as an unwanted carrier component in the modulator and as a DC offset in the demodulator. The imbalance of the individual mixers may be compensated for in the integrated IQ device by applying an appropriate DC bias at the I and Q terminals. Suppression of carrier leakage in this way introduces temperature dependence due to the diode characteristics and temperature compensation of the bias or temperature stabilization of the whole circuit will be necessary. Tuning of the balance by passive components is certainly preferable at least to the extent where only fine adjustments are required.

The signals to and from the mixers are given such relative phases that the unwanted sidebands from each mixer (image frequency bands) cancel while the desired sidebands add in phase. This is shown in Fig. 4 and 5. Differences in the signals from the two mixers (differential phase and amplitude errors) cause the sideband suppression to be less than perfect. Common variations of the signals with frequency cause a frequency dependent complex (amplitude and phase) transfer function.

Correction for some of the above mentioned deficiencies can be implemented using the digital signal generation and processing [3]. Such techniques are presently being studied in a Ph.D. study at Electromagnetics Institute, The Technical University of Denmark.

One of the more difficult components is the hybrid needed to combine the two modulated signals from the balanced mixers in the modulator and to split the input signal to the mixers in the demodulator. Odd (relative to the reference signal frequency) amplitude imbalance between the two channels of this hybrid cannot be corrected neither at baseband nor at the modulated signal. The small relative bandwidth encountered in the homodyne approach is believed to reduce the problems with these errors.

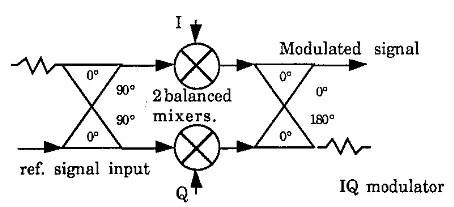

Figure 4. IQ modulator principle

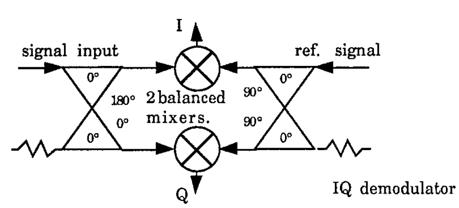

Figure 5. IQ demodulator principle

MEASUREMENTS

Direct measurement of the parameters in question is difficult because the signals to be compared are at different frequencies and the accuracy of normal laboratory equipment is not sufficient to verify whether the specifications are met.

Measurements in the 0.1 dB and 1° range at 300 MHz and 5.3 GHz must be treated with caution. The equipment used for these measurements was never specified to such accuracies.

Some accurate information can be obtained from a modulator/demodulator pair (back to back) but this is not sufficient to characterize the system performance. Since a nonlinear element, namely the HPA (a TWT with a FET preamplifier), must be included in the final system, the modulator and demodulator must be characterized individually.

Two sets of measurements for the modulator are given below. The one (named "analog method") has been acquired by conventional measurement equipment (vector voltmeter, spectrum analyzer etc.) while the other (named "digital method") has been acquired by utilization of the digital signal generator and data acquisition of the radar system with a carefully characterized nonlinear element introduced to give the information needed to separate the measured deficiencies between those caused by the modulator and those caused by the demodulator.

The two measurement methods do not give exactly the same information. Furthermore disagreements are noticed between some of the results which may be caused by minor modifications of the 300 MHz modulator after the analog measurements were performed, or by the fact that the measurement uncertainty of the analog method is fairly large relative to the quantities to be determined. The "digital" method is in the process of verification but some important results exist already. The parameters measured for the 300 MHz modulator have been used for pre-distortion of the digitally generated IQ signals and this caused a substantial reduction of the unwanted sideband. The main purpose of disclosing these incomplete measurements is not to present record breaking specifications but to substantiate that the higher frequency components may do the job as good as the lower frequency components.

The frequency dependent parameters are given as peak-peak values over the -50/+50 MHz frequency band except where otherwise noted. Where appropriate, the frequency dependence of the deficiencies are decomposed in static, linear slope, and ripple components.

MODULATION AT 300 MHz AND 5.3 GHz

In order to study the possibilities of direct modulation at 5.3 GHz an IQ modulator was build for comparison with the 300 MHz SAR modulator. Some key figures are given in table 1 and 2. Some of the parameters mentioned are defined in the two previous sections.

Reference signal frequency	300 MHz	5.3 GHz
Signal input level, I and Q (note 1)	-15 dBm	-15 dBm
50 dB carrier suppression below signal, vs. ΔT	5°C	5°C
Signal/noise in 100 MHz band, incl. amplifier	50 dB	68 dB
Signal/harmonics etc	45 dB	45 dB
Static phase error	< 1°	9°
Differential phase error, -50 / +50 MHz	1°	<1°
Differential amplitude error, -50 / +50 MHz	0,05 dB	0.2 dB
Transfer function amplitude, -50 / +50 MHz	1.0 dB	0.25 dB
Conversion loss	amplifier	6 dB
Output filter for oscillator and image suppression	critical	no need

Table 1. Modulators compared, analog method.

note 1: Actually the 300 MHz modulator requires a higher input level due to a feedback stabilized input stage but the level indicated is corrected for this fact to give the same voltage at the base-emitter junctions.

The 300 MHz modulator is built using double balanced transistor multipliers. The circuits has been carefully tuned to reduce carrier leakage and static (quadrature) phase error. The performance is just adequate for fulfilment of the design goals of the SAR since the temperature is stabilized within a few degrees. The signal to noise ratio is adequate although rather low compared to that of the 5.3 GHz unit. The high noise level is believed to be caused by a high internal conversion loss masked by the amplification of the transistors.

The 5.3 GHz modulator is built using single balanced diode mixers based on 180° ring hybrids. It is interesting to note that the first version of that modulator had two deficiencies namely a rather high diode offset and carrier leakage directly from the reference signal input to the modulator output. The carrier could be suppressed by imposing 35 mV DC bias on the I and Q inputs but a 50 dB carrier suppression was maintained only within a 0.5°C temperature range. Even that modulator could be applied provided temperature compensation was implemented. However, considerable improvements was obtained by replacing one diode and tuning the carrier leakage out. The results from this are given in tables 1 and 2.

Reference signal frequency		300 MHz	5.3 GHz
Baseband and even RF amplitude imbalance:			
	slope	0.12 dB	0
	ripple	0.16 dB	< 0.02 dB
Baseband and RF phase imbalance:	slope	1°	1°
	ripple	1.5°	0.2°
Odd RF amplitude imbalance:	slope	0.4 dB	0.2 dB
	ripple	0.2 dB	<0.05 dB
Phase imbalance:	static	2.5°	10.5°
	slope	1°	0.4°
	ripple	2°	0.2°

Table 2. Modulators compared, digital method.

The 5.3 GHz unit has a better transfer function than the 300 MHz unit (and that is further improved since the output filter can be omitted) but a worse differential amplitude if the older 300 MHz measurements are still valid. The differential amplitude of 0.2 dB over the band causes a contribution to ISLR of -38.7 dB which is just acceptable (leaving some head room for other contributions to ISLR) even without digital correction.

Comparing the results of the digital method reveals that the 5.3 GHz unit is the better everywhere except for the static phase imbalance which may be tuned out at the reference signal hybrid.

DEMODULATION AT 300 MHz AND 5:3 GHz

The 300 MHz demodulator is built using double balanced diode mixers. Tuning of the mixers have not been attempted but the DC offset of the IQ outputs has been compensated. The performance is just adequate for fulfilment of the design goals of the SAR.

The 5.3 GHz modulator is built using single balanced diode mixers based on 180° ring hybrids. Actually the same components has been used as for the modulator measurements. Some key figures are given in table 3.

The differential phase is obviously a problem for the 300 MHz unit at the higher modulation frequencies while it is better than the 5,3 GHz unit for the differential amplitude. The 5.3 GHz unit will give adequate performance as it is and improvements are expected to be possible. For broadband applications the high frequency unit is certainly the better of the two.

In addition to the components discussed so far, it is important to remember the amplifiers (DC included) and low pass filters at the I and Q outputs. These are needed in both homo- and heterodyne systems and the symmetry of the two channels is critical for the performance.The measurements for the 300 MHz unit has been performed for the mixers alone and for the complete unit including the filters and amplifiers at the I and Q outputs. Some of the information on the IQ demodulator has thus been determined indirectly .

Reference signal frequency	300 MHz	5.3 GHz
Signal input level (note 2)	-9 dBm	-12 dBm
Signal level at each balanced mixer	-15 dBm	-15 dBm
DC offset variation: ΔT for 0.2 mV change	20°C	21°
Signal/noise in 100 MHz (IQ amplifiers included)	68 dB	68 dB
Signal/IM products	>50 dB	>55 dB
Static phase error, tuned	<1°	<1°
Differential phase error, -30 / +30 MHz	2°	
Differential phase error, -50 / +50 MHz (note 3)	7°	0.5°
Differential amplitude error, -50 / +50 MHz	<0.05 dB	0.2 dB
Transfer function amplitude, -50 / +50 MHz	0.08 dB	0.4 dB
Conversion loss of each balanced mixer	6.1 dB	6 dB
Number of RF filters required	2	1

Table 3. Demodulators compared, analog method.

note 2: The input signal levels reflects the fact that a resistive power divider is used in the 300 MHz input.

note 3: The differential phase error for the 300 MHz demodulator is given with the filters included and is expected to be much lower for the demodulator itself but an reliable estimate of that cannot be performed from the available data.

CONCLUDING REMARKS

The discussion above has focussed on fixed carrier frequency application and do not help those wanting to explore the inherent broadband capability of the homodyne principle. Broadband image rejection mixers with high suppression of the carrier and the image frequency band may be very difficult to manufacture but in modern systems it will be feasible to adjust the offset together with the frequency and that might be the solution if frequency agility is required.

For civilian radar applications frequency agile systems are usually of less importance, and is probably without any interest as long as passive array antennas are used because the antenna in that case will limit the usable bandwidth severely.

The implementation of pre-distortion in the digital signal generator is a useful way of improving the performance, and has proven [3] to give good results for errors in the modulator of the heterodyne system and it is expected that this technique will be important in relation to homodyne systems which can then achieve very good performance.

More important, however, is the result that the homodyne system is capable of as good a performance as the heterodyne system when broadband radars at fixed frequency are considered.

ACKNOWLEDGEMENT

The individual modulators and demodulators have been designed, constructed, and documented in the master theses of L. Theil Hansen, O. Stender Nielsen, J. Harding Thomsen, and F. M. Olsen. F. M. Olsen has performed the 5.3 GHz analog measurements while A. Netterstrøm has developed the digital measurement method and has performed the measurements with that.

REFERENCES

[1] Butler, M.B.N.
Radar Applications of SAW dispersive Filters, Proc. IEE, Vol. 127, Pt.F, No. 2, April 1980

[2] Hoft, D.J. and Fishwich, M.B.
Analog Waveform Generation and Processing, Electronic Progress, Vol. 17, No. 1, pp 2-16, spring 1975 (published by Raytheon Co., Lexinton, Mass.)

[3] Netterstrøm, A.
Digital Correction of Analog Signal Processing Errors, Int. Conf. on Radar 89, 24-28 April 1989, Paris, Vol 1, pp 313-318

[4] Madsen, S.N., Christensen, E. L., and Skou, N.
KRAS - A Danish High Resolution Airborne Radar, Proc. of the 16'th Int. Congress of the Int. Soc. of Photogrammetry and Remote Sensing, ISPRS Kyoto July 1988

[5] Skou, N., Madsen, S.N., and Christensen, E. L.
The TUD C-band SAR, Proc. of the 1988 IGARSS' Symposium, Vol. II, 12.-16. September 1988, Edinburgh

[6] Madsen, S.N., Christensen, E. L., and Skou, N.
A New C-band SAR for ERS-1 Underflights, Radar-90, IEEE 1990 Int. Radar Conf, 7-10 May 1990, Arlington, VA, USA.

AUTHORS' MAILING ADDRESS
Electromagnetics Institute, Technical University of Denmark
Building 348, Lundtoftevej 100, DK 2800 Lyngby, Denmark
Phone +45 42 88 14 44, Fax +45 45 93 16 34, Telex 37 529